

Gamma-ray line from radiative decay of gravitino dark matter

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Abstract

We study radiative decay of gravitino dark matter with trilinear R-parity violations. We show that the branching ratio of the decay of gravitino into monochromatic photon can be large enough to explain the observed gamma-ray line from the Galactic centre in the Fermi-LAT data without producing too much continuum gamma-ray and anti-proton flux. This scenario is realized when the mass of sfermions and the trilinear R-parity violating coupling are $O(1 - 10)$ TeV and $O(10^{-7} - 10^{-6})$ respectively.

1 Introduction

Recent studies on the four-year Fermi data have found excess of 130 GeV gamma-ray line from the Galactic Center (GC) [1, 2, 3, 4, 5, 6]. There have been many papers studying various possible explanations (instrumental effects [7, 8, 9, 10], pulsar wind effects [11] etc.) of this signal but it is most interesting if it is to be interpreted as a dark matter (DM) signature [12, 13]. If this interpretation is correct, the 130 GeV gamma-ray line is the long-awaited signature of non-gravitational interactions of particle DM.

In order to explain the 130 GeV gamma-ray line with particle DM, a rather large branching ratio of DM annihilating or decaying into monochromatic photon is required, i.e. $\text{Br}(\text{DM} \rightarrow \gamma) \gtrsim 0.01$ [14, 15, 16]. Otherwise, DM to fermion and gauge boson annihilation or decay channels would produce too much continuum gamma-ray and conceal the line signal. Moreover, anti-proton flux produced by these channels are constrained by cosmic-ray observations [17]. However, in many cases, the branching ratio of DM annihilating or decaying into photons is suppressed because DM does not couple directly to photon. It has been shown that for monochromatic photon production channel with standard model (SM) particles running in the loop, annihilating DM is typically in tension with the 130 GeV gamma-ray line scenario [18].

We consider decaying DM in this letter. Specifically, we study gravitino DM in R-parity violating (RPV) supersymmetric (SUSY) models [19, 20]. ^{#1} With bilinear RPV operators, it is difficult to realize the gamma-ray line scenario [14]. We complement the previous study by considering trilinear RPV operators. With sfermion masses of $O(\text{TeV})$, the tree-level decay rate of gravitino is suppressed and the radiative decay can explain the 130 GeV gamma-ray line. Furthermore, there are no overproductions of continuum gamma-ray and anti-proton flux.

The model considered here is consistent with cosmology. The lightest SUSY particle of the MSSM (MSSM-LSP) decays into gravitino or other SM particles due to RPV interactions before the big-bang nucleosynthesis (BBN) begins. This prevents the late decay of the MSSM-LSP from spoiling the success of the BBN. We also note that the requirement of relatively heavy sfermions does not contradict with the recent discovery of the 126 GeV Higgs-like boson at the LHC [22, 23]. In fact, negative results on SUSY searches at the LHC and a rather heavy Higgs boson favor SUSY models with large sfermion masses.

The rest of the letter is organized as follows. First, we will discuss the theoretical framework of our model. Then, we discuss general aspects of its phenomenology. Next, we elaborate how it can explain the 130 GeV gamma-ray line. Before we comment on our model and make conclusion, we study cosmological aspects of the model.

^{#1} Another viable decaying SUSY DM candidate, axino, has been studied in Ref. [21].

2 Gravitino dark matter with R-parity violation

2.1 Framework

Let us write down the relevant interaction lagrangian of gravitino:

$$\begin{aligned}\mathcal{L}_{int} = & -\frac{i}{\sqrt{2}M_{\text{Pl}}} \left[(D_\mu^* \phi^{i*}) \bar{\psi}_\nu \gamma^\mu \gamma^\nu P_L \chi^i - (D_\mu \phi^i) \bar{\chi}^i P_R \gamma^\nu \gamma^\mu \psi_\nu \right] \\ & -\frac{i}{8M_{\text{Pl}}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda^{(\alpha)a} F_{\nu\rho}^{(\alpha)a} + \mathcal{O}(M_{\text{Pl}}^{-2}).\end{aligned}\quad (2.1)$$

$\phi^i, \chi^i, \psi_\nu, \lambda^{(\alpha)a}$ are sfermion, the corresponding fermion, gravitino and gaugino, respectively. D_μ is the covariant derivative and $F_{\nu\rho}^{(\alpha)a}$ is the field strength tensor. P_L (P_R) is the projection operator projecting onto left-handed (right-handed) spinors. All interactions are suppressed by the reduced Planck mass $M_{\text{Pl}} \simeq 2.4 \times 10^{18} \text{ GeV}$.

Next, we write down the superpotential related to RPV [24]. In the most general form, it is

$$W = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k + \mu_i L_i H_u, \quad (2.2)$$

where summation among the indices $i, j, k = 1, 2, 3$ which denote the lepton and quark generation is implicitly assumed. L_i, E_i, Q_i, D_i, U_i and H_u are chiral superfields of lepton doublet, lepton singlet, quark doublet, down-type quark singlet, up-type quark singlet and up-type Higgs doublet, respectively. The first three terms lead to trilinear RPV while bilinear RPV arises due to the last term. $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ are dimensionless parameters and μ_i is a parameter with mass dimension one. Hereafter, we will work in the basis where $\mu_i L_i H_u$ is rotated away from the superpotential. This is done by redefining L_i and the down-type Higgs superfield H_d as $L'_i = L_i - \epsilon_i H_d$ and $H'_d = H_d + \epsilon_i L_i$ with $\epsilon_i \equiv \mu_i/\mu$, where μ is the higgsino mass parameter in the MSSM superpotential $\mu H_u H_d$. Due to this redefinition, SUSY-breaking soft terms, including those corresponding to the bilinear RPV,

$$-\mathcal{L}_{soft} = (B H_u H_d + B_i \tilde{L}_i H_u + m_{L_i H_d}^2 \tilde{L}_i H_d^* + \text{h.c.}) + m_{H_d}^2 |H_d|^2 + m_{\tilde{L}_i}^2 |\tilde{L}_i|^2 + \dots, \quad (2.3)$$

where \tilde{L}_i is the scalar component of the chiral superfield L_i , undergo transformation as well. In the following, primes of the redefined fields and soft terms are omitted to tidy up our notations. In this basis, sneutrinos' vacuum expectation values (VEVs) are typically non-zero. By minimizing the scalar potential of sneutrino (including the SUSY-breaking soft terms), the VEVs are found to be

$$\langle \tilde{\nu}_i \rangle = -\frac{m_{L_i H_d}^2 \cos \beta + B_i \sin \beta}{m_{\tilde{\nu}_i}^2} v. \quad (2.4)$$

$\tan \beta \equiv v_u/v_d$ is the ratio of the VEVs of the up- and down-type Higgs fields. $m_{\tilde{\nu}_i}^2$ is the sneutrino mass and $v \equiv \sqrt{v_u^2 + v_d^2} \simeq 174 \text{ GeV}$.

Note that trilinear RPV terms, LLE and LQD , are also generated by the field redefinition. They are absorbed into the parameters λ_{ijk} and λ'_{ijk} . In summary, we work with the superpotential

$$W = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k \quad (2.5)$$

and non-zero sneutrino VEVs, which we parametrize as $\kappa_i \equiv \langle \tilde{\nu}_i \rangle / v$.

2.2 Some phenomenological implications and constraints

In this subsection, we consider general phenomenological aspects of our framework. First, we focus on trilinear RPV couplings. Allowing both lepton and baryon number violation would lead to proton decay with a very short lifetime. Moreover, as will be discussed in detail in the next subsection, gravitino DM's leptonic decays are preferred over hadronic decays in order to explain the 130 GeV gamma-ray line. Therefore, we assume baryon number conservation by choosing $\lambda''_{ijk} = 0$.

Another bound on trilinear RPV couplings arises from cosmological considerations. λ_{ijk} and λ'_{ijk} has to be small enough to prevent wash-out of the baryon asymmetry before the electroweak transition. The couplings are, generically [25, 26, 27, 28],

$$\lambda_{ijk}, \lambda'_{ijk} \lesssim 5 \times 10^{-7} \left(\frac{M_{\text{SUSY}}}{1 \text{ TeV}} \right)^{1/2} \quad (2.6)$$

where M_{SUSY} is the masses of squarks or sleptons. Other bounds on trilinear RPV couplings are known to be less stringent [24].

We can no longer distinguish between the lepton doublet and the up-type Higgs doublet under bilinear RPV. Sneutrino VEVs that mix leptons with gauginos are induced. Specifically, neutrinos mix with neutralinos whereas leptons mix with charginos. Bilinear RPV's constraints can be deduced from neutrino masses generated by sneutrino VEVs. Masses of neutrino are $m_\nu \sim g^2 \langle \tilde{\nu} \rangle^2 / m_{\tilde{B}}$, where $m_{\tilde{B}}$ is the mass of bino [29, 30, 31]. For gaugino masses of $O(\text{TeV})$, $\kappa_i = \langle \tilde{\nu}_i \rangle / v \lesssim 10^{-6}$ is required by experimental bounds on neutrino masses.

In the following, we will study the scenario where trilinear RPV is dominant and bilinear RPV is negligible. We note that even if bilinear RPV is absent at tree level at a certain energy scale, renormalization group evolution will generate the bilinear terms at some other energy scale. Unfortunately, we have not found any model that can naturally explain the smallness of bilinear RPV in the literature. On the flip side, if the 130 GeV gamma-ray line can really be interpreted as a signature of gravitino DM with trilinear RPV, it should inspire model building efforts towards a theory with such characteristic in the future.

2.3 Trilinear R-parity violation-dominant scenario

Gravitino undergoes three-body decay via trilinear couplings at the tree level. As will be explained in the next paragraph, we will consistently be working with the LLE RPV

operators. For leptonic decay with an intermediate mass $m_{\tilde{\tau}_R}$, the decay rate is [20]

$$\Gamma(\psi_{3/2} \rightarrow \bar{\tau}\nu_i e_j) \simeq \frac{|\lambda_{ij3}|^2}{90(32)^2\pi^3} \frac{m_{3/2}^7}{M_{\text{Pl}}^2 m_{\tilde{\tau}_R}^4}. \quad (2.7)$$

The full analytical result has been worked out in [32]. Gravitino undergoes one-loop radiative decay as well [33]. The decay rate scales as

$$\Gamma(\psi_{3/2} \rightarrow \gamma\nu_i) \sim \frac{\alpha\lambda_{ijj}^2 m_{3/2} m_j^2}{M_{\text{Pl}}^2} \quad (2.8)$$

when the sfermion masses are large compared to gravitino and lepton masses. The radiative decay rate is proportional to the fermion mass. Therefore, RPV couplings involving the third generation of fermion gives the largest contribution. We also note that the radiative decay is approximately independent of the mass of sfermion running in the loop of the decay amplitude. It can be understood from the amplitude of the interaction that involves the first two terms of Eq. (2.1). These terms carry a derivative of the sfermion field that brings a momentum flow proportional to the largest loop-mass to the vertex. It balances out the contribution of the sfermion mass from the sfermion propagator.^{#2} Hence, by increasing the mass of the sfermion and taking $m_{3/2} \simeq 260\text{GeV}$, one can get the branching ratio $\Gamma(\psi_{3/2} \rightarrow \gamma\nu_e)$ that is large enough to explain the Fermi line. The dependence of this branching ratio on the sfermion mass is shown in Fig. 1.

The apparent 130 GeV gamma-ray line can be explained by a decaying DM of lifetime τ_{DM} that satisfies

$$\tau_{\text{DM}}/\text{Br}(\text{DM} \rightarrow \gamma\nu) = (1-3) \times 10^{28} \text{ sec} \quad (2.9)$$

and branching ratio $\text{Br}(\text{DM} \rightarrow \gamma\nu) \gtrsim 0.01$ [14]. In this region of parameter, astrophysical constraints from diffuse gamma-ray [34] and neutrino spectra [36, 35] are also satisfied. As an illustration of our model, we choose the sfermion masses to be $m_s \simeq 3\text{TeV}$. The branching ratio of the radiative decay is $\text{Br}(\text{DM} \rightarrow \gamma\nu) \simeq 0.18$. In order to conciliate with Eq. (2.9), the RPV coupling are needed to be $\lambda \equiv \lambda_{133} \simeq 6 \times 10^{-7}$.

We note that a large range of parameters (DM lifetime and branching ratio) is excluded by the PAMELA anti-proton data for gravitino DM with bilinear RPV [14]. We do not have such concern for gravitino with *LLE* RPV operators because no anti-proton is produced from its decay.

We now discuss several cosmological constraints on our model. Under trilinear RPV, the MSSM-LSP, which we assume to be the bino, may decompose into SM particles via tree-level decay. The decay rate is

$$\Gamma_{\tilde{B} \rightarrow SM} = \frac{5\lambda^2\alpha}{16\pi^2\cos^2\theta_W} m_{\tilde{B}}\psi(m_s/m_{\tilde{B}}). \quad (2.10)$$

^{#2}See Ref. [33] for a detailed description of the radiative decay amplitude.

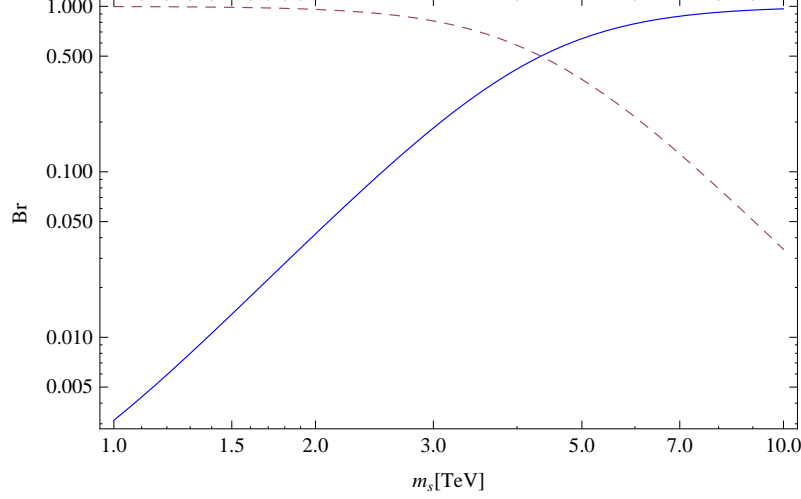


Figure 1: Dependence of branching ratios of gravitino decay via λ_{133} on the intermediate sfermion mass m_s . Here, the intermediate sfermions are assumed to be the left-handed and right-handed staus. Their masses are degenerate and take the value m_s . The decay modes are tree-level decay (dashed, red) and radiative decay (blue). The mass of the gravitino is $m_{3/2} \simeq 260\text{GeV}$.

α and θ_W are the fine structure constant and the Weinberg angle respectively. We have assumed that the masses of left-handed and right-handed stau are degenerate, i.e. $m_s \equiv m_{\tilde{\tau}_R} = m_{\tilde{\tau}_L}$. The function $\psi(y)$ is defined as

$$\psi(y) = \int_0^{1/2} dx \frac{x^2(1-2x)}{(1-2x-y^2)^2}. \quad (2.11)$$

For $m_s/m_{\tilde{B}} \lesssim 10$ and $m_{\tilde{B}} \sim 1\text{TeV}$, λ has to be greater than 10^{-9} so that $\Gamma_{\tilde{B} \rightarrow SM}^{-1} \lesssim 1\text{sec}$. We see that in the region of parameter of interest, BBN is unaffected as bino decays much earlier than 1 sec.

MSSM-LSP decays into gravitino as well. The decay rate is [37]

$$\Gamma_{\tilde{B} \rightarrow \psi_{3/2}}^{-1} \simeq 5 \times 10^4 \text{sec} \left(\frac{m_{\tilde{B}}}{1\text{TeV}} \right)^{-5} \left(\frac{m_{3/2}}{260\text{GeV}} \right)^2. \quad (2.12)$$

Bino that decays into gravitino contribute to the relic abundance of gravitino. However, since $\Gamma_{\tilde{B} \rightarrow SM}^{-1} \ll \Gamma_{\tilde{B} \rightarrow \psi_{3/2}}^{-1}$, only an insignificantly small fraction of bino decays into gravitino. Hence, bino's contribution to the gravitino relic abundance is negligible.

The thermal relic abundance of gravitino is [38, 39, 40, 41]

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{T_R}{10^{10} \text{GeV}} \right) \left(\frac{m_{3/2}}{260 \text{GeV}} \right)^{-1} \left(\frac{m_{\tilde{g}}}{1 \text{TeV}} \right)^2, \quad (2.13)$$

where T_R is the reheating temperature and $m_{\tilde{g}}$ is the gluino mass. Since thermal leptogenesis requires $T_R \gtrsim 10^9$ [42], our scenario is consistent with thermal leptogenesis for $m_{\tilde{g}} \sim O(\text{TeV})$.

3 Discussion and Conclusion

Several comments are in order before we conclude. Gravitino also decays into gauge bosons via *LLE* RPV couplings but branching ratios of these channels are generally equal or smaller than that of the radiative decay [43]. This does not alter our results as we still obtain branching ratio large enough to explain the Fermi gamma-ray line at large sfermion masses without violating astrophysical constraints.

The morphology of the observed gamma-ray line excess favors annihilating DM but decaying DM is acceptable as well [14, 44]. More data is required before one confirms or rules out the possibility of explaining the gamma-ray line with decaying DM.

We now briefly discuss the prospect of detection in collider. The lifetime of the MSSM-LSP is around $10^{-6} - 10^{-4}$ sec and thus if produced, it will decay outside of the detector. Events with missing energy can be recognized as the collider signature.

In conclusion, we have shown that gravitino dark matter with trilinear R-parity violation is capable of explaining the 130 GeV gamma-ray line. Models with the *LLE* R-parity violating coupling are especially advantageous since there is no overproduction of anti-proton flux, in contrast with the bilinear R-parity violating scenario. Other astrophysical constraints are also satisfied. Furthermore, our model is consistent with cosmology (big-bang nucleosynthesis and thermal leptogenesis). The requirement of sfermion masses of $O(\text{TeV})$ is well-motivated by the 126 GeV Higgs boson and negative searches for supersymmetric particles.

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